Support Platform and Communications to Manage Cooperative AUV Operations

T. R. Cuff
University of Idaho, Department of Electrical and Computer Engineering

R. W. Wall
University of Idaho, Department of Electrical and Computer Engineering

Abstract – **For the testing of control and communications algorithms in cooperative behavior, a fleet of autonomous underwater vehicles (AUVs) is under development by the University of Idaho. This paper discusses one piece of the puzzle in this fleet: the communications module to manage multiple agents. The communications system provides multiple modes of operation. Different communications mediums to and from the vehicle support these modes of operation. The tools supplied by the different modes of operation assist the researchers in developing communications, control algorithms, and valuable hardware systems.**

I. INTRODUCTION

The modern battlefield is evolving into a profusion of machines. Technology replaces manpower to perform dangerous tasks in an effort to reduce wartime casualties. The United States Navy, in the interest of using technology in the form of autonomous underwater vehicles (AUVs), desires vehicles for mine countermeasures (MCMs) and the mapping of landing zones. A single AUV has proven to be successful in performing these operations [1]. The University of Idaho is performing research and development of a fleet of test platforms of which the prototype is shown in Fig. 1. These test platforms are used by the researchers to explore communications and control algorithms for a fleet of AUVs maneuvering in formation cooperatively searching for mines and mapping landing zones. The benefits of using multiple AUVs include increased reliability through redundancy, increased area coverage in a shorter amount of time, and higher quality of measurements through overlapping coverage [2].

The primary motivation in the construction of a fleet of autonomous underwater vehicles is the development of algorithms. The primary vision of the research platform is to minimize the algorithm development time. The mission cycle, shown in Fig. 2, reduces development time by providing an organized methodology to algorithm development. The mission cycle starts with an idea or concept. The researchers simulate their ideas for algorithms in a computer environment. From a successful simulation they create mission files to upload onto the vehicles. The vehicles are put into the water to

Fig. 1. The University of Idaho prototype vehicle.

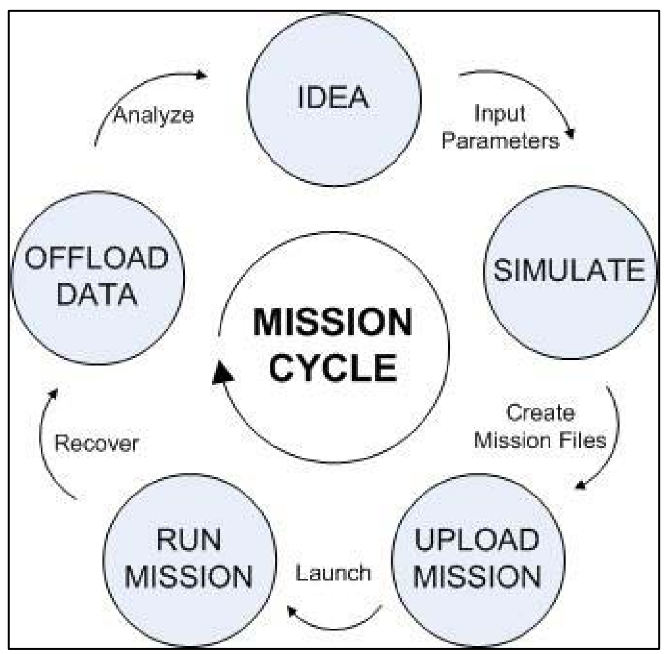

Fig. 2. The vision of the mission cycle.

run the programmed missions. While running a mission the vehicles collect data and store it in internal memory. When the mission is concluded the data is retrieved and analyzed. The analyzed data provides measures to assess performance and

The authors gratefully acknowledge the support of the Office of Naval Research, which supported this work under the awards "Communication and Control for Fleets of Autonomous Underwater Vehicles" No. N00014-04-1-0506, "Fabrication of a Fleet of Mini-AUVs" No. N00014-04-1-0803, and "Developing Fleets of Autonomous Underwater Vehicles" No. N00014-05-1-0674.

1-4244-0138-0/06/$20.00 ©2006 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Support Platform and Communications to Manage Cooperative AUV Operations**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Idaho,Department of Electrical and Computer Engineering,Moscow,ID,83844**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

insights into ways improve algorithms for another mission cycle.

This paper focuses on the vehicle's communications module and its external communications channels as well as the proprietary fleet management software used in surface operations for the test platform. The communications module provides three modes of operation supported by three communication mediums external to the vehicle and one internal. The internal channel leads to a distributed network supported by Ethernet using TCP/IP and UDP protocols. The distributed control network passes messages between microprocessor nodes within the vehicle. As this is the topic of another paper [3], little else will be said about the internal network.

The external channels provide three methods for communicating with the world outside the vehicle. One method, referred to as the real-time communications channel, provides real-time fleet management of the vehicles while on the surface and between autonomous missions. Another method configures the vehicles prior to running an autonomous mission and downloads the data gathered after an autonomous mission is complete. The user connects through web pages, served by the vehicle itself, to configure systems and download data. The final method communicates through an acoustic modem. The modem serves two purposes: it acts as a sensor for navigation by calculating position based off of Long BaseLine (LBL) active navigation and it provides the medium for communications between vehicles operating in autonomous mission mode.

II. REAL-TIME COMMUNICATIONS

Between missions the user needs the ability to control the vehicle into a position away from obstacles. The real-time communications link and proprietary control software provides this function, using the keyboard, mouse, or joystick for user input. Other functions include the real-time display of telemetry and surface position information, the ability to start and abort missions, and the data display and control of up to eight AUVs.

A. Hardware (Fig. 3.)

A pair of model 9XStream [4] wireless radio modems made by MaxStream, provides the wireless communications link. The 9XStream model operates at a frequency of 900MHz and transmits data at 9600 baud. A Yagi high-gain, directional antenna on the base station provides a maximum range of 32 kilometers, line-of-sight and in optimum conditions. In some cases the radio signal is capable of penetrating the surface of the water to a depth of 0.5 meters that proved invaluable during the initial design phase of the vehicle.

On the vehicle, a RCM3000 [5] microcontroller, made by Rabbit Semiconductor, provides the link from devices internal to the vehicle to devices external. The RCM3000 (RCM stands for Rabbit Core Module) operates at 29.4 MHz, has one megabyte of memory evenly divided between flash and SRAM, and makes available an Ethernet port and other pins

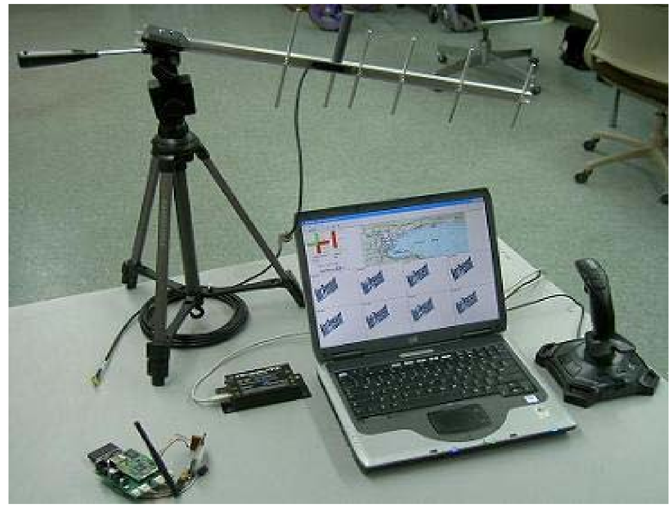

Fig. 3. The real-time communications hardware.

for serial communications. As mentioned earlier, the Ethernet port provides connectivity to the internal distributed network.

A laptop computer, running the Windows XP operating system (OS), a joystick, and a global positioning system (GPS) receiver complete the hardware and act as the base station. The joystick is an optional tool because all joystick controls have a related keyboard command (the joystick is favored over keyboard control for its obvious ease of use). A laptop, as opposed to a desktop computer, provides mobility and over two hours of battery operation in case a power source becomes unavailable. This seemingly minor feature has the benefit of allowing users to locate and recover vehicles when external power is not available.

B. Software

The real-time communications software on the vehicle conveys messages between devices on the internal distributed network and the radio modem. Every 500 milliseconds the data from the sensors, along with mission state and local x- and y-coordinates, gets formed into packet. This packet is tagged with a message identifier and vehicle identification number and transmitted via the radio modem. There are currently three types of messages received by the radio modem from the laptop. The first kind of message controls fin positions and motor speed. These messages are sent directly to the motor/servo controller. The other two messages are the start and abort mission messages, which are sent to the autonomous vehicle controller, or the 'brain' of the vehicle. The start mission message contains a number identifying the number of the mission to start. How these different missions get into the vehicle controller is mentioned later. Abort mission messages obviously are passed to the controller to tell it to stop the currently running mission, which is useful if the user notices the vehicle behaving inappropriately and the radio modem is still in contact with the vehicle.

The software Graphical User Interface (GUI) is a Windows OS executable. The inputs to the program come

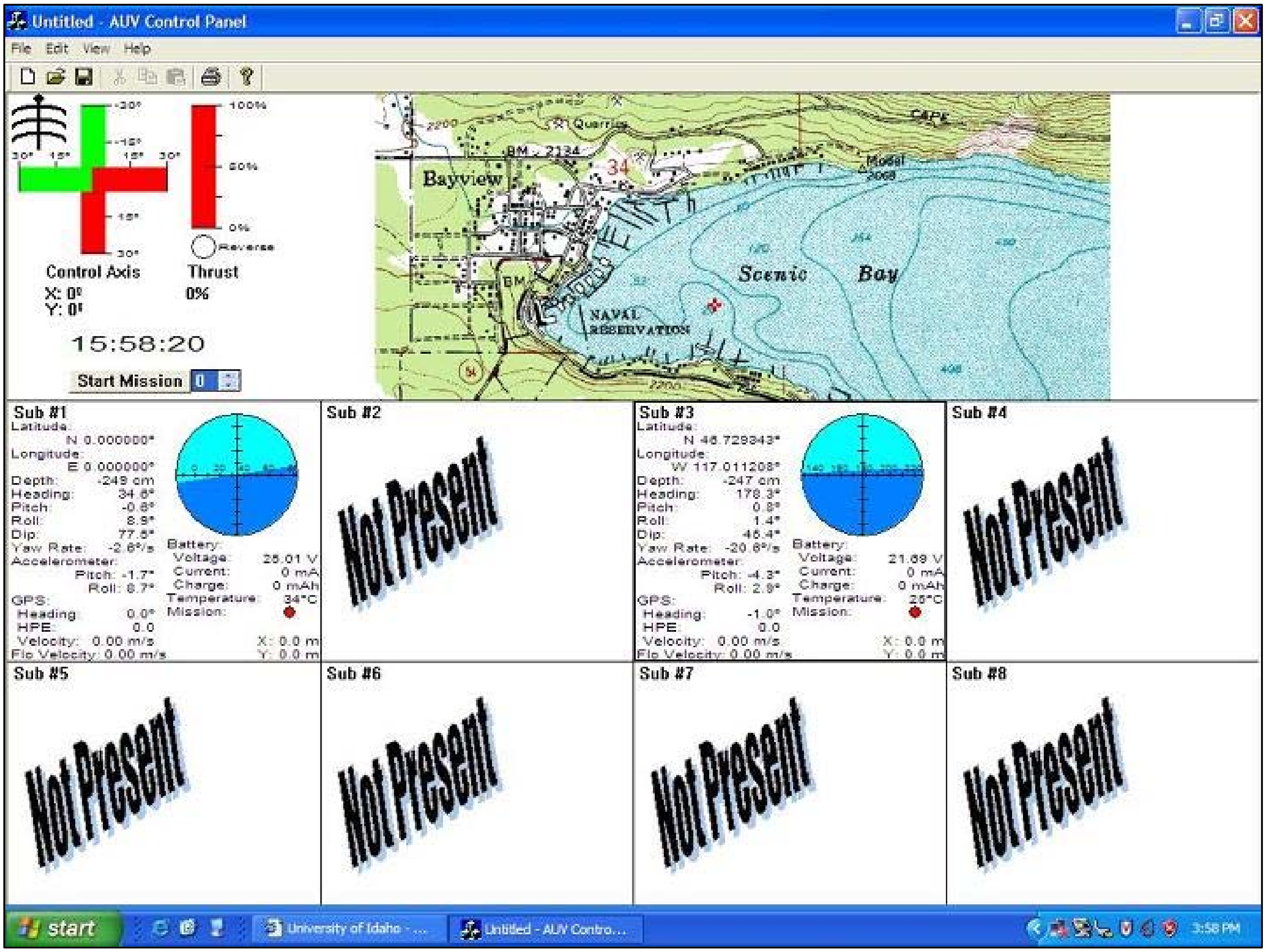

Fig. 4. Screenshot of AUV Control Panel software.

from the mouse, keyboard, joystick, and the radio modem attached via the Universal Serial Bus (USB). The outputs are the display and the control packets that are sent out the radio modem.

C. Features

Fig. 4 is a sample screenshot of the AUV Control Panel while in action. The incoming telemetry data for two vehicles are displayed with vehicle #3 having the focus for control commands. The thicker border around the data indicates the focus for control commands. The features and their benefits for the AUV Control Panel are now enumerated using Fig. 4, as an example.

1) Real-time display of telemetry data

When the vehicles are active and on the surface, they transmit specific data indicating position, orientation and internal telemetry. If the vehicle and the GUI are configured for the same network (256 networks available), the same hopping channel (seven channels available), and within range of the antenna, this data is displayed on the screen. Theoretically, the GUI can display data for 14336 vehicles (7 hopping channels × 256 networks × 8 vehicles per network). This is in theory, but the reality of it is that there are limitations in the radio frequency channel. Fig. 4, shows the reception of data from vehicles #1 and #3 that are on network zero using hopping channel one. The telemetry data includes:

- GPS information - latitude, longitude, heading, velocity, and Horizontal Position Error (HPE).
- Depth.
- Compass information – heading, dip, pitch, and roll.
- Yaw rate.
- Accelerometer information – pitch and roll (used in gyrocompass graphic).
- Velocity from a flow sensor.
- Environmental information – battery voltage, current, and state of charge; temperature inside the vehicle.
- Mission mode state – out, in, or initializing.

- Local x-coordinate and y-coordinate in meters as determined by LBL.
- Gyrocompass graphic – visual feedback of vehicle heading (from compass), pitch, and roll (from accelerometers).

2) Real-time vehicle control

Researchers need the ability to control the vehicles during launch of and recovery from missions. To this end, the Control Panel sends control messages, via the real-time wireless communications, to the vehicles. Fig. 4, shows telemetry data arriving from two different vehicles. Either of these vehicles or both can be controlled with joystick or keyboard commands when they have the focus. The user sets the focus to individual vehicles to control them into the starting point for missions and selects multiple vehicles when the user starts multiple vehicles on the same mission or controls the vehicles concurrently.

3) Commanded feedback

Commanded rudder and planes positions along with commanded engine power (represented as a percentage) are displayed in the upper left corner of the screen. The antenna symbol in the extreme upper left corner indicates that the radio is actively sending and receiving data. A digital clock of the current system time assists in tracking mission start times. Specifying a mission number in the scroll box (Fig. 4) and selecting the 'Start Mission' button on the screen will send the message to start the mission. Pulling the trigger on the joystick sends an abort mission command. All previously mentioned controls have equivalent keyboard commands and affect the selected vehicle(s) equally.

4) Top-side tracking

Every vehicle has the capability of reporting its GPS data when its GPS receiver is unobstructed from the satellites. This GPS data, along with the GPS data for the base station, helps to locate the position(s) of the vehicle(s) relative to the base station. As of the writing of this paper, this feature is still under development and the image in the upper left corner is merely a placeholder for where the user will eventually see the GPS information displayed. The ability to locate the vehicles at mission end assists in their recovery.

III. MISSION CONFIGURATION AND DATA DOWNLOAD

With the vehicle in the laboratory or on the dock in the staging area, researchers need the ability to configure the vehicle and download its mission data log. A wireless Ethernet connection with web pages served up by the vehicle itself provides this function. Using a wireless form of access to the vehicle's data reduces wear and tear on the seals that keep the vehicle watertight. The short range of wireless Ethernet doesn't permit real-time, long-range control of the vehicles but the high-speed connection permits fast data download while the vehicle is close.

Fig. 5. Master (left) and slave (right) controller hardware. The master controls the wireless Ethernet.

A. *Hardware (Fig. 5.)*

A Linksys model WCF12 [6] wireless CompactFlash card provides the wireless Ethernet link. The CompactFlash plugs into a Type 1 slot and makes available a link using the 802.11b standard, operating at 2.4GHz.

On the vehicle, a Rabbit Semiconductor RCM3100 [7] microcontroller provides the link between a slave microcontroller (the same microcontroller used for the previously described real-time communications) and the wireless CompactFlash card. The RCM3100 Rabbit Core Module operates at 29.4 MHz, has one megabyte of memory evenly divided between flash and SRAM, and has pins for connecting to a slave device and an external memory device. The wireless CompactFlash card gets accessed like an external memory device.

Any properly configured computer with a wireless Ethernet card can acquire the ad hoc connection. The same laptop providing real-time communications accesses the wireless Ethernet.

B. *Software*

A special software packet driver library for controlling the pins of the CompactFlash card is available from Rabbit Semiconductor. This driver provides the necessary functions for using most any TCP/IP communications protocol. The wireless Ethernet uses Hypertext Transfer Protocol (HTTP) for serving up web pages and File Transfer Protocol (FTP) for data download. Most of the web pages are created statically (HTML files are created before compile time) and compiled into the flash memory. Other web pages are created dynamically at run-time, using current data from inside the vehicle. For example, the different runs that are stored in the data log are displayed in a table format created at run-time so that the user can select a link to choose a log for FTP download.

As mentioned before, any properly configured computer can link to the wireless network card and access information from a vehicle. The user needs only to start a web browser and

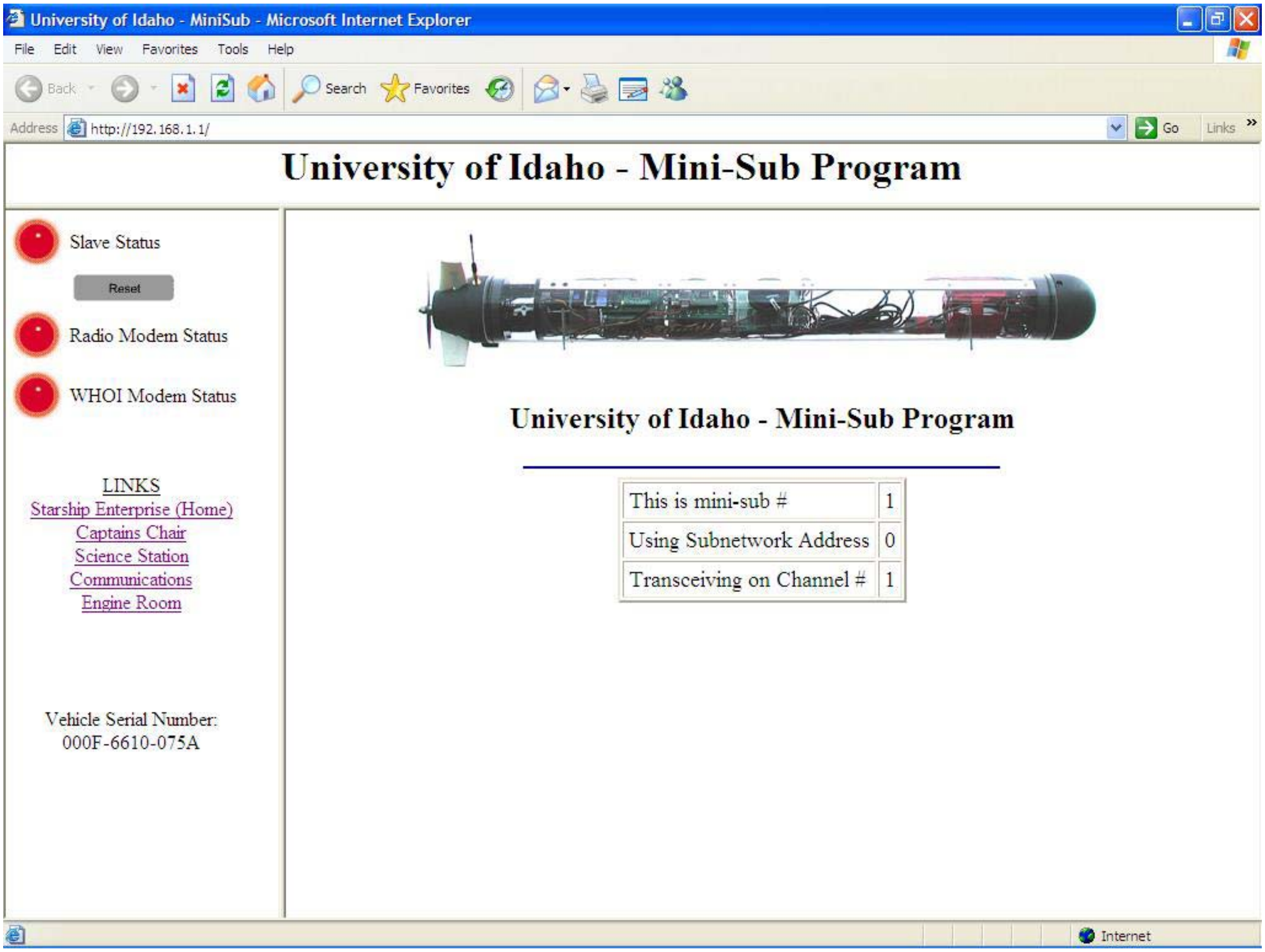

Fig. 6. Screenshot of home page for vehicle #1.

link to the static IP address of the vehicle. Once on the home page, the user can click on links in navigation bar (left side of Fig 6.) to access other information stored on the vehicle. No special software is required on the PC to access this information.

C. Features

Figs. 6,7, are example screenshots of actual web pages that are served by a vehicle. Fig. 6, is the home page while Fig.7, is an example of the data download page. The features and benefits of the varying web pages are now enumerated using the Figs. 6,7, as reference.

1) Navigation Bar

The navigation bar is available in the left column of every page and makes available links to the different 'departments' on the vehicle. A 'department' defines an area of the vehicle where information (configuration or status) resides. For example, at the 'department Science Station' link resides the status for the depth sensor and the ability to calibrate the depth sensor.

A set of indicator lights shows the status of the slave, the radio modem, and the acoustic modem. Clicking the reset button on the screen does a power off reset of the slave communications. This feature proved invaluable during development when a coding error for the internal network occasionally caused the slave processor to stop working. The last bit of information on the navigation bar is the serial number for the vehicle. This value is simply the Media Access Control (MAC) address for the wireless Ethernet card, which is the unique 48-bit address, assigned to all Ethernet devices.

2) Home Page

The home page identifies the project by displaying a picture of the vehicle. The home page also displays the current communications configuration. As mentioned in the real-time communications section, the vehicle number, the network, and the address are all used to identify this vehicle to the AUV Control Panel. The vehicle number is also used to identify this vehicle on the acoustics network (described later).

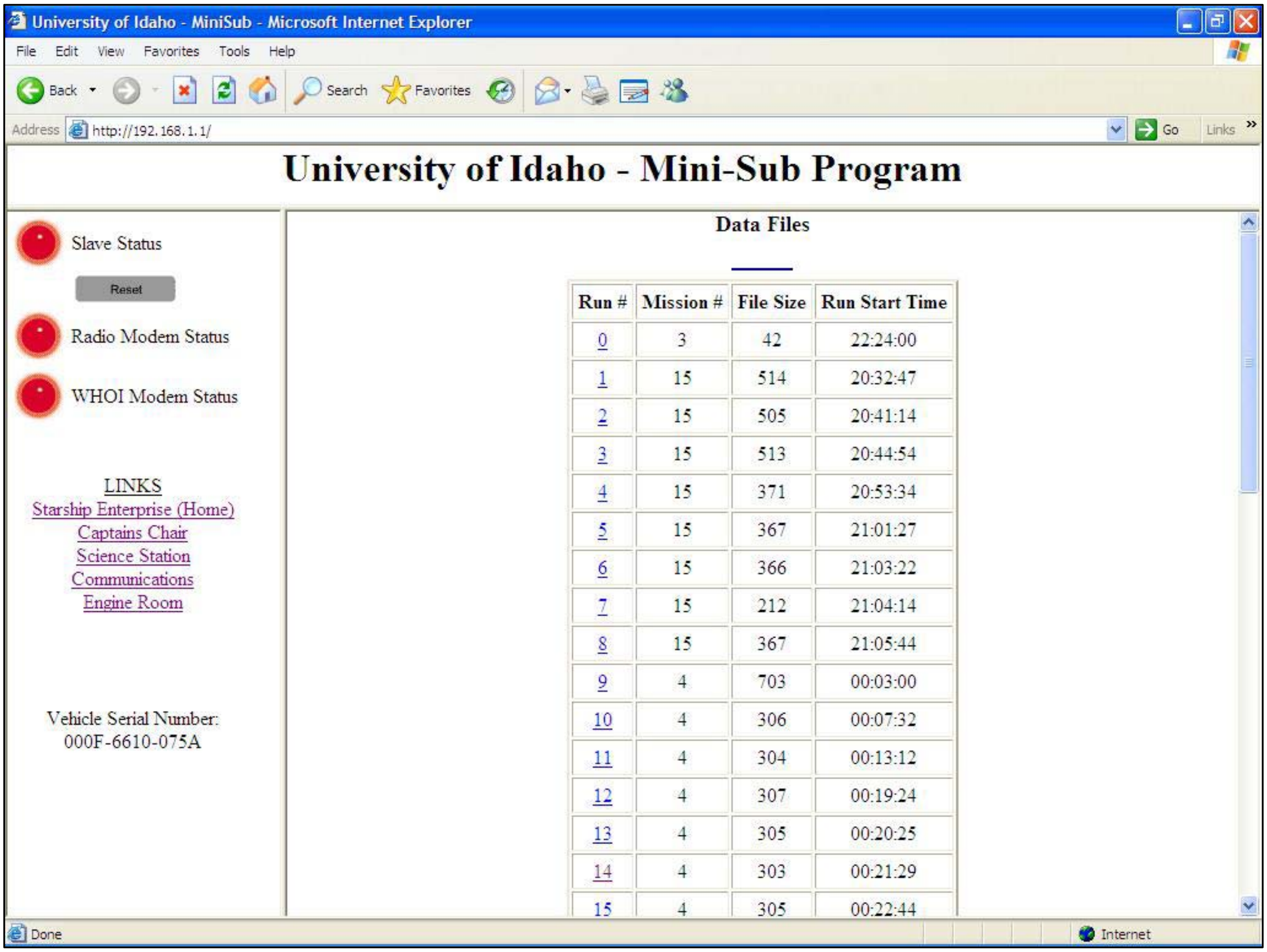

Fig. 7. Screenshot of data download page.

3) The Captain's Chair Link

The link to the 'Captain's Chair' takes the user to another page for mission upload, data download, or erasing the memory in the data log. To erase the memory, the reset button on the web page is clicked, while mission upload and data download requires following the links.

On the mission upload page the user can select a file from the computer's file system and upload it into the vehicle's memory. Current versions of the controller use a hard-coded parameter file on the AUV for missions but future releases of the vehicle will use this mission file for its parameters. Recall the mission number mentioned in the real-time communications section; this number (which again is currently hard coded) will eventually be tagged to the filename. This number also identifies the mission in the data log (Fig. 7).

From the data download link the user can download the data captured during a mission. The data download web page (Fig. 7) lists the run number, the mission number, the size of the data file in blocks (128 bytes per block), and the GPS time at the start of the mission. Clicking the mouse pointer on the link represented by the run number will start an FTP download of the data for that run.

4) Science Station Link

The 'Science Station' calibrates some of the sensor devices. The depth sensor (pressure guage) is reset to zero when the vehicle is floating on the surface. Also, the pitch sensor is reset to zero when the vehicle is leveled with a level.

5) Communications Link

The communications web page provides links for entering buoy positions used for navigation, and for configuring the radio and acoustic modems. The vehicle uses the buoy positions for LBL active navigation (described later). Configuration values for the radio modem that are available to be set through the web page are the same ones displayed on the home page. In the current version of the software the acoustic modem parameters and most of the radio modem parameters are hard-coded in the firmware, whereas future versions will allow the parameters to be set through this web page.

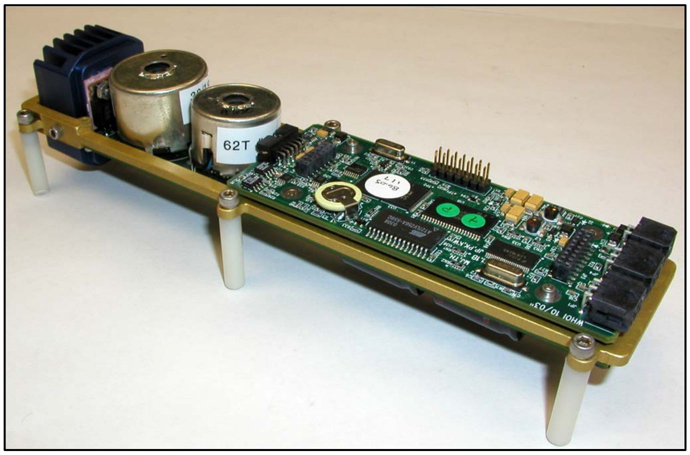

Fig. 8. The WHOI acoustic micromodem for communication and navigation.

6) Engine Room

Early in development, the designer's needed the ability to change the fin trim settings in real-time during vehicle tests. To help the vehicle maintain a correct course, the fin positions are zeroed to compensate for defects in manufacturing. Another value that can be set in the 'Engine Room' is the control surface coupling coefficient, which is used to reduce rolling in the turns.

IV. UNDERWATER COMMUNICATIONS AND NAVIGATION

The emphasis of this research is cooperative behavior in control and communications algorithms. The previously mentioned mission files define the control algorithms. Communications algorithms define how the vehicles cooperate in the low bandwidth environment of the underwater acoustic channel. The final piece to the puzzle defines how the vehicle uses LBL active underwater navigation.

A. Hardware

A Wood's Hole Oceanographic Institute (WHOI) acoustic Micro-Modem [8] (Fig. 8) and an omni-directional ceramic transducer are used for communicating acoustically underwater. The WHOI acoustic modem provides for both communications and navigation underwater [9]. To navigate, the vehicle calculates its position relative to the known location of surface buoys. The same microcontroller that runs the real-time communications also operates the acoustic modem.

B. Software

The WHOI Micro-Modem uses a command set that follows the National Marine Electronics Association (NMEA) 0183 Standard for interfacing marine electronics [8]. This standard defines messages as sentences that begin with '$' and five characters and has comma-separated parameters. These messages are sent from and read by the firmware on the slave microcontroller (referred to as the host). The host must perform two tasks: relay communications messages and process navigation messages. The timing for these two tasks is hard-coded into the firmware, but in future revisions it will be changed through a web page.

1) Acoustic communications

To begin transmission of a communications message every vehicle sends out a network cycle initialization packet. A notification message is sent from the modem to the host of every vehicle that receives the message. It is also echoed back to the sender of the message. Among other parameters, the message contains the source and the destination addresses and a command parameter for identifying broadcast messages. The reception of this message signals the host into transmit or receive mode dependent on the aforementioned parameters.

If the host is identified as the source of the message, then a request for data to transmit is sent to the controller node via the internal network. When the data to be transmitted arrives from the controller processor, it is immediately sent to the modem.

On the other hand, if the command parameter identifies the message as a broadcast and the host is not the source or if the host is the destination for the message, then the host is put into receive mode. While in receive mode, the host accepts and relays to the controller node the next message received. After receiving a message or after a timeout, the host is taken out of receive mode until the next cycle initialization packet reception.

2) Acoustic navigation

The acoustic navigation is performed using Long BaseLine (LBL) active navigation pings. At intervals determined by the firmware, the host sends an active navigation ping message to the modem. The modem then pings the buoys. The response message contains parameters identifying time-of-flight information from each buoy. Time-of-flight along with information about the buoy positions is all that is needed to determine the vehicle's position in a local coordinate system [10]. This information is sent to the controller for navigation purposes.

V. RESULTS

From the vehicle's first test at the University of Idaho's swimming pool in May of 2005, the communications module has helped the developers to design algorithms needed for autonomous control. The joystick interface gave researchers the ability to quickly design a dive routine, vector control, and an optimized surface operation through squat control. The human-in-the-loop joystick actions were replaced by autonomous controls that were programmed as missions. This was how the autonomous controls were fine-tuned.

Throughout development and hundreds of missions, new features have been added to the communications module to aid developers. Originally there was just the real-time control interface with joystick control and telemetry data for one vehicle. The wireless control required a communications configuration web page for the radio modem on the vehicle. Then there was a need to save the telemetry data to a file for post analysis while the data-logging feature of the vehicle was

still under development. The next thing added was a web page for trim settings and coupling coefficient to improve control performance. After that came the need to zero certain sensors, improving the accuracy of sensor readings. At the end of Summer 2005, the catch phrase was 'dockside downloading.' This feature was added to speed development while reducing wear-and-tear on the watertight seals. The most recent addition is multiple vehicle control and telemetry data.

The communications module has proven valuable throughout multiple tests. The vehicle has survived over a dozen pool tests, a test in a local flooded clay pit, and six tests in the waters of Lake Pend Oreille, Idaho. The most recent test took the vehicle to the Acoustical Research Detachment of the Naval Surface Warfare Center, Carderock Division (ARD-NSWCCD) in Bayview, Idaho. It was programmed to navigate a path while broadcasting position information. This data was captured by acoustic equipment. With the vehicle reprogrammed as a follower, the captured message was played back into the water. The follower vehicle successfully traced a path offset from the simulated leader broadcast. Future tests will involve other vehicles currently in production rather than playback.

VI. CONCLUSION

The communications module successfully fills the need for multiple modes of operation in an AUV test platform. The AUV Control Panel allows researchers to manually control multiple vehicles into start position and recovery. It also interfaces with the vehicles to put them into mission mode or abort them out of mission mode. Through the web pages, researchers can configure the vehicle, zero the sensors, upload missions, and download data. Lastly, and most importantly, the communications module provides the ability to communicate and navigate acoustically while the vehicle operates autonomously.

VII. REFERENCES

[1] L. Freitag, M. Grund, C. von Alt, R. Stokey, and T. Austin, "A shallow water acoustic network for mine countermeasures operations with autonomous underwater vehicles," in *Proc. Oceans 2005,* Washington DC, 2005.

[2] M. Stojanovic, L. Freitag, J. Leonard, and P. Newman, "A network protocol for multiple AUV localization," in *Proc. IEEE Oceans 2002,* vol. 1, pp. 604-611, 2002.

[3] G. Beidler and R. Wall. "Low cost distributed control for autonomous vehicles," in *Proc. Oceans 2006*, Singapore, 2006, in press.

[4] 9XStream, MaxStream, Inc. [Online]. Available: http://www.maxsream.net/products/xstream/oem-rf-module.php, 2005.

[5] RCM3000, Rabbit Semiconductor. [Online]. Available: http://www.rabbitsemiconductor.com/products/rcm3000/, 2006.

[6] WCF12, Linksys, [Online]. Available: http://www1.linksys.com/products/product.asp?grid=33&scid=36&prid=434, 2005.

[7] RCM3100, Rabbit Semiconductor. [Online]. Available: www.rabbitsemiconductor.com/products/rcm3100/, 2006.

[8] L. Freitag and M.Grund. Micromodem Software Interface Guide. [Online]. Available: http://acomms.whoi.edu/micromodem/, 2005.

[9] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI Micro-Modem: an acoustic communications and navigation system for multiple platforms," in *Proc. Oceans 2005,* Washington DC, 2005.

[10] L. Freitag, M. Johnson, M. Grund, S. Singh and J. Preisig, "Integrated acoustic communication and navigation for multiple UUVs," in *Proc. Oceans 2001*, Honolulu, HI, pp. 2065-2070, 2001.

[11] S. Mupparapu et al., "Autonomous monitoring and control (ASMAC) – an AUV fleet controller," in *Proc. Autonomous Underwater Vehicles, 2004 IEEE/OES* June 2004.

[12] C. Carignan, J. Lane, and D. Akin, "Control architecture and operator interface for a free-flying robotic vehicle," in *Proc. IEEE Conf. Systems, Man and Cybernetics* Aug 2001.

[13] V. Riquad, "First steps in Infremer's autonomous underwater vehicle program – A 3000m depth operational survey AUV for environmental monitoring," in *Proc. of The Fourteenth International Offshore and Polar Engineering Conf.,* May 2004.